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Calculational Methods for Predicting Thermal Radiation Signals at Satellites

Radiation Research Associates, Inc.
Fort Worth, Texas

6 MAY 1977

Topical Report

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This report describes the calculational methods developed to predict thermal radiation signals at satellite-borne detector systems resulting from radiation emitted by point isotropic thermal radiation sources positioned within the atmosphere. The time-dependent atmospheric transport data currently available from POLO Monte Carlo calculations are described and the methods available for convoluting the time dependent atmospheric transport data with the wavelength and time-dependent emission from thermal radiation sources are outlined.

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I. INTRODUCTION

This paper presents a review of the current status of data and methods used by Radiation Research Associates to calculate the radiation power available to satellites at synchronous altitudes that result from the visible and near infrared radiation produced by detonations of nuclear weapons. General flow and interdependence of the system is shown in Fig. 1.

POLO is a Monte Carlo computer code (Ref. 1) which can be used to estimate both the direct and the time-dependent scattered atmospheric transmissions of radiation in or near the visible range from a monochromatic, point isotropic source to a point detector. Results of POLO runs are stored on tape and constitute the data pool. Data from this pool, in combination with a source term, provide the information necessary to calculate the thermal power at a detector. Convolution of the source and transmission data is performed with one of two codes: TMTAU or POLY. Several auxiliary codes are available to manipulate data at various points in the system, only two of which are shown in Fig. 1. One of two curve-fit codes is available for use in converting transmission data from discrete points to a continuous function if the TMTAU program is to be used. The RF2POLY code can be used to reduce the time mesh of the source data and to convert the results to appropriate units if a RADFLO-generated source is to be used.

The remainder of this paper describes the extent of the data pool, some of the modeling parameters and a brief discussion of the TMTAU and POLY programs.

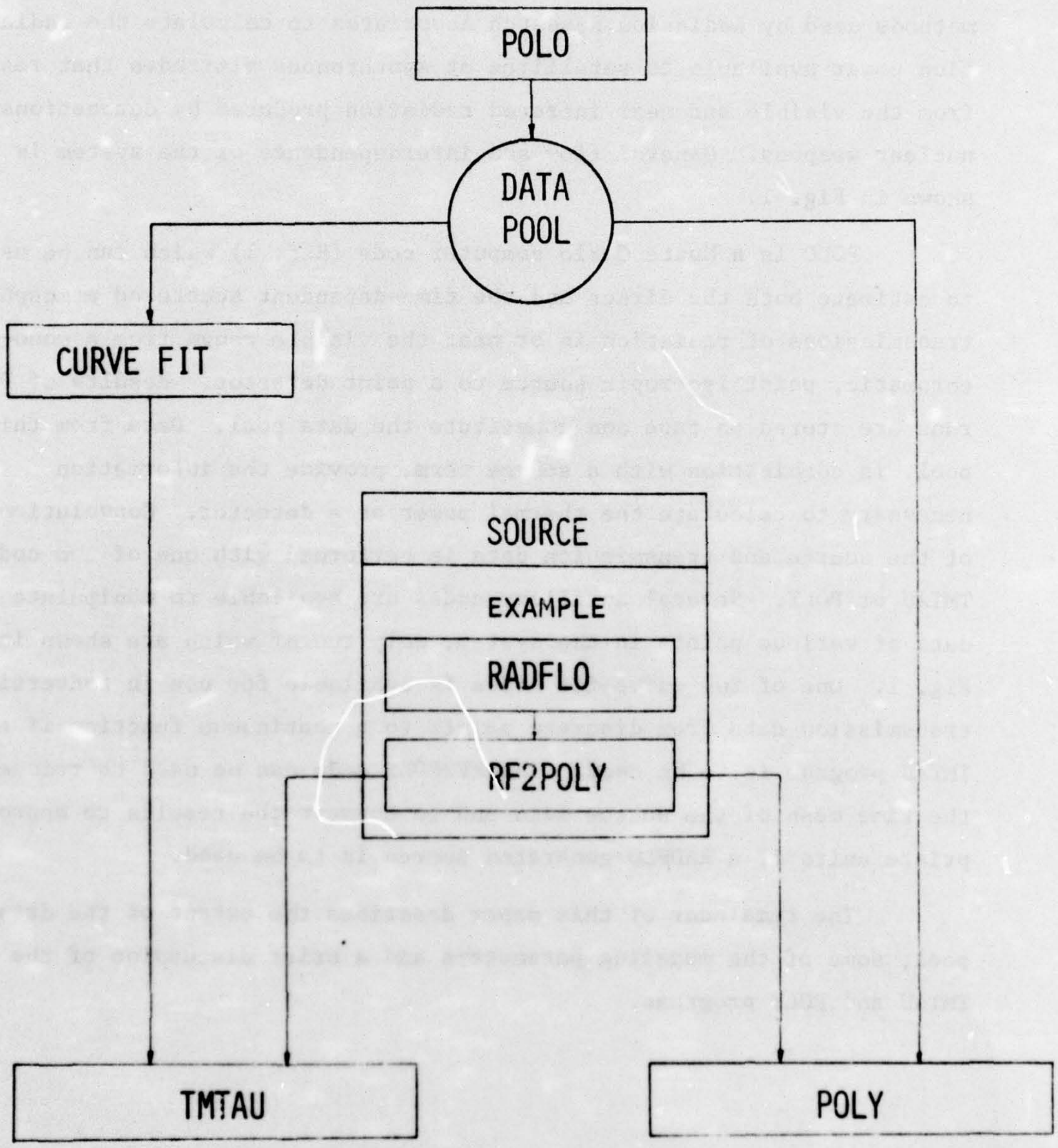


Fig. 1. General Flow of the Computational System for Computing Thermal Power at Satellite-Based Detection Systems

II. EXISTING DATA POOL

Since the POLO-calculated data which constitute this data pool are best defined by certain parameters and since the number of possible parameter combinations is large, a group of POLO problems, hereafter referred to as a standard set, is defined in Fig. 2.

A standard set contains POLO problems run for (1) only one model atmosphere (defined by ground meteorological range); (2) ten values of a ground albedo ranging from 0.0 to 0.9 in increments of 0.1; (3) three values of the source wavelength, namely, .4278, .75, and 1.07 microns; (4) eight detector look angles (the angle between a source radial and a line connecting the source subpoint and the detector), namely, 0, 30, 45, 60, 70, 75, 80, and 90 degrees; (5) a detector altitude of 35,800 km; and (6) four source altitudes. Three of the four source altitudes will always be .5, 3, and 10 km. The fourth source altitude will be 100 meters for the model atmosphere having a 40-km meteorological range and 1 meter for all others.

A standard set of POLO data exists for model atmospheres having meteorological ranges of 3, 10, 25, and 40 km. POLO data which are available in excess of these four standard sets are described in the remainder of this section.

Two extensions to the standard sets are shown in Table I where XX indicates existence of the data. For the 25-km meteorological range atmosphere, four look angles below the horizon (91, 92, 93, and 94 degrees) were used for source wavelengths of 0.4278 and 0.75 microns. These problems (for .5-, 3-, and 10-km source altitudes only) were used to augment a standard set and verify graphic predictions. For the 40-km meteorological range atmosphere, problems with eight look angles (the same as used in a standard set) for "non-standard" wavelengths of 0.5 and 0.6 microns were used to augment a standard set. Impetus for these problems was to determine the error

1. One model atmosphere

2. Ten values of the ground albedo (0.0 - 0.9)

3. Three source wavelengths: 0.4278, 0.75, and 1.07 μm

4. Detector look angles of 0, 30, 45, 60, 70, 75, 80, and 90 degrees

5. Satellite altitude of 35800 km

6. Four source altitudes of 1.0m or 100m, 0.5 km, 3 km, and 10 km

Standard sets of POLO data exist for atmospheres with meteorological ranges of 3, 10, 25, and 40 km

Fig. 2. Standard Set of Polo-Generated Data

TABLE I. EXTENSIONS TO STANDARD SETS: TYPE I

		λ = .4278			λ = .5				λ = .6				λ = .75			λ = 1.07
	Standard Set	XX			XX				XX				XX			XX
25 km MR		hs											hs			
	θ_ℓ	.5	3.	10									.5	3.	10	
	91	XX	XX	XX									XX	XX	XX	
	92	XX	XX	XX									XX	XX	XX	
	93	XX	XX	XX									XX	XX	XX	
	94	XX	XX	XX									XX	XX	XX	
40 km MR					hs				hs							
	θ_ℓ				.1	.5	3.	10	.1	.5	3.	10				
	0				XX	XX	XX	XX	XX	XX	XX	XX				
	30				XX	XX	XX	XX	XX	XX	XX	XX				
	45				XX	XX	XX	XX	XX	XX	XX	XX				
	60				XX	XX	XX	XX	XX	XX	XX	XX				
	70				XX	XX	XX	XX	XX	XX	XX	XX				
	75				XX	XX	XX	XX	XX	XX	XX	XX				
	80				XX	XX	XX	XX	XX	XX	XX	XX				
	90				XX	XX	XX	XX	XX	XX	XX	XX				

incurred when a wavelength (λ) dependent analytic expression of the form

$$f(\lambda) = \exp \sum_{i=0}^{n} a_i \lambda^i$$

was used for only three wavelengths. This form is used in TMTAU with $n = 2$ and in TMTAURF with $n \geq 2$. Errors incurred by using $n = 2$ in the above equation have not been severe. As an illustration of possible errors, plots of a curve for $n = 2$ (dashed) and $n = 3$ (solid) are shown in Fig. 3. The solid curve in Fig. 3 includes data for 0.5-micron wavelength. Although an obvious error would result from using $n = 2$ in this example, the errors in practice are small and $n = 2$ would suffice. The use of source data from RADFLO, however, have necessitated an increase in the number of wavelengths used to define the source. TMTAU programs are constructed such that transmission data must be defined for the same wavelengths as the source. Modifications to TMTAU (i.e., TMTAURF) to include more wavelengths were primarily made for this reason.

Extensions of all four standard sets to include look angles of 83, 85, and 87 degrees were made to eliminate the error incurred by graphic interpolation of the standard set data to look angles around 85 degrees. As an example of this situation, Fig. 4 shows the variation with look angle of the flux at a satellite from a source at 10-km altitude, in a 25-km meteorological range atmosphere, and at 1.07 microns wavelength. Results from the standard set show the direct flux and the scattered flux for 0.0 and 0.9 ground albedos as a function of ($1 - \cos\theta_L$), where θ_L is the look angle. Including data for look angles of 83, 85, and 87 degrees (shown in Fig. 5) demonstrates the graphic interpolation errors which could have occurred. The dashed lines in Fig. 5 represent the graphic interpolation from the curves given in Fig. 4 for look angles between 80 and 90 degrees.

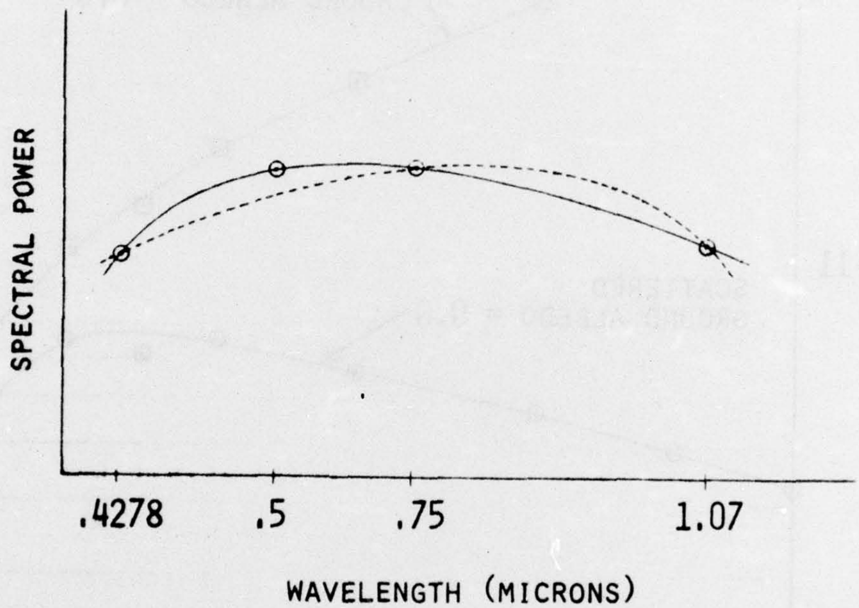
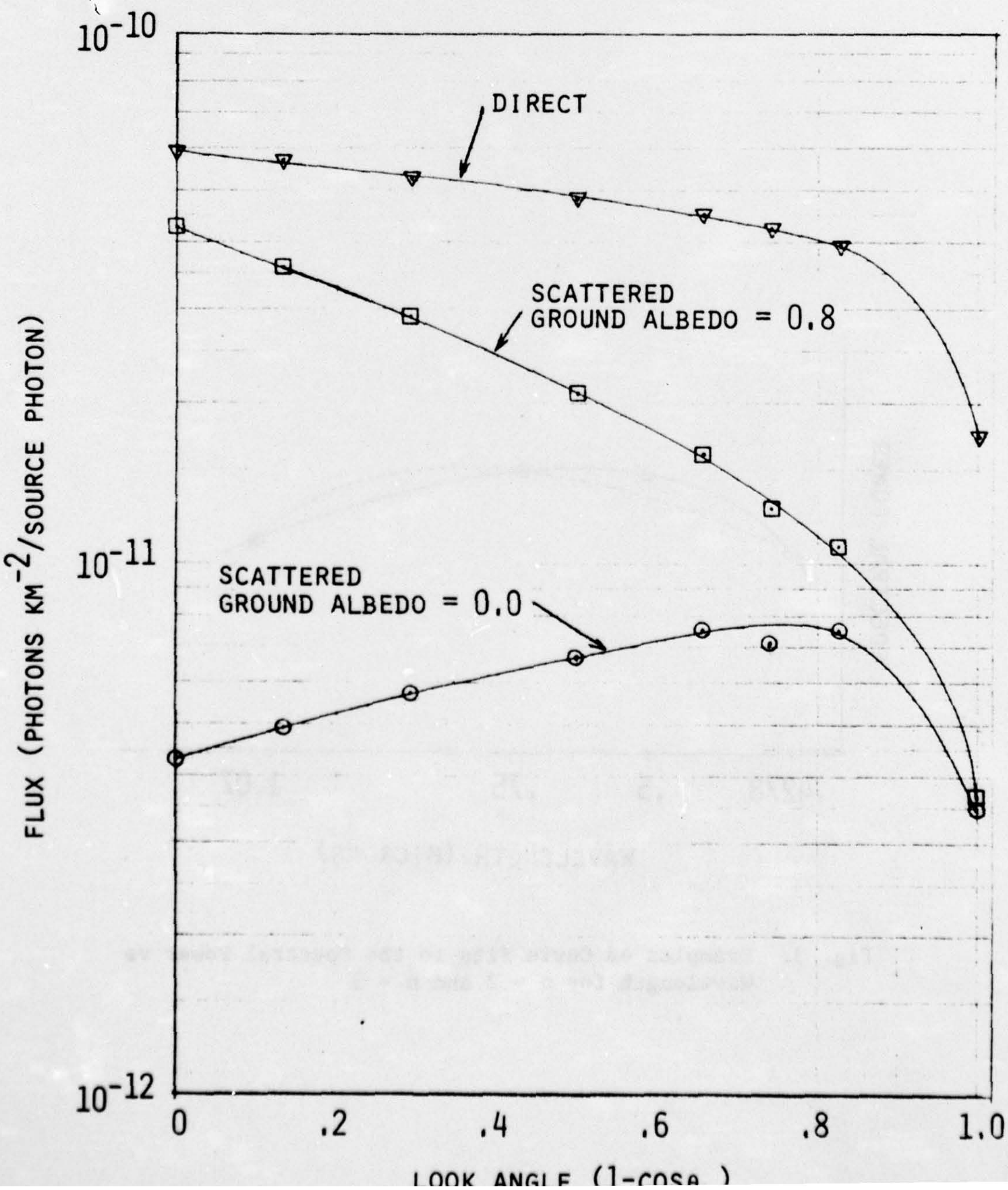


Fig. 3. Examples of Curve Fits to the Spectral Power vs Wavelength for n = 2 and n = 3



DIRECT
SCATTERED GROUND ALBEDO = 0.8
SCATTERED GROUND ALBEDO = 0.0
FLUX (PHOTONS KM^{-2}/SOURCE PHOTON)
10^{-10}
10^{-11}
10^{-12}
0
.2
.4
.6
.8
1.0
LOOK ANGLE (1-COSθ)

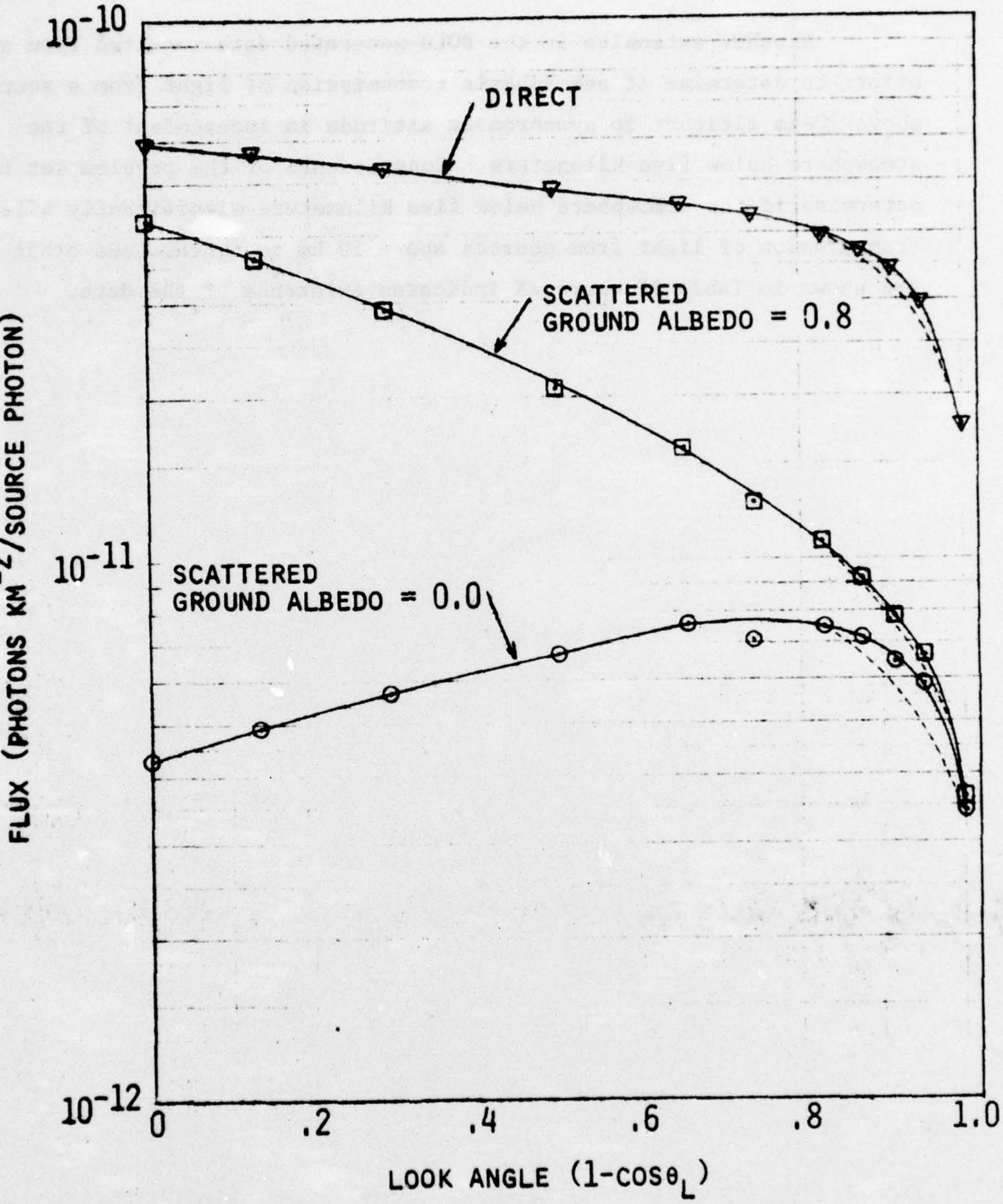


Fig. 5. Flux from a 10-km Altitude, 1.07 μm Wavelength Source in a 25-km Meteorological Range Atmosphere for 11 Look Angles

Another extension in the POLO-generated data resulted from an effort to determine if atmospheric transmission of light from a source above 10-km altitude to synchronous altitude is independent of the atmosphere below five kilometers. Constituents of the problem set to determine if the atmosphere below five kilometers significantly affects transmission of light from sources above 10 km to synchronous orbit are shown in Table II where XX indicates existence of the data.

TABLE II. PROBLEM PARAMETERS FOR SOURCES AT 20 AND 40 KM ALTITUDE

	3km MR				25km MR				40km MR					
	.75		1.07		.75		1.07		.4278		.75		1.07	
	hs				hs				hs					
θ_L	20	40	20	40	20	40	20	40	20	40	20	40	20	40
0	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX
15	XX	XX			XX	XX			XX	XX	XX	XX	XX	XX
30	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX
45	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX
60	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX
65	XX	XX			XX	XX			XX	XX	XX	XX	XX	XX
70	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX
75	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX
77.5	XX	XX			XX	XX			XX	XX	XX	XX	XX	XX
80	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX
82	XX	XX			XX	XX			XX	XX	XX	XX	XX	XX
84	XX	XX			XX	XX			XX	XX	XX	XX	XX	XX
86	XX	XX			XX	XX			XX	XX	XX	XX	XX	XX
88	XX	XX			XX	XX			XX	XX	XX	XX	XX	XX
90	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX
95	XX	XX			XX	XX			XX	XX	XX	XX	XX	XX

III. MODEL ATMOSPHERES

Atmospheric modeling for atmospheres having meteorological ranges of 3, 10, and 25 km was done for 0.4278, 0.75, and 1.07 microns in 1971. The atmospheric model for the 40-km meteorological range model atmosphere was generated in 1975 for wavelengths of 0.4278, 0.5, 0.6, 0.75, and 1.07 microns and contains certain refinements. All models used the molecular density profiles reported in the U. S. Standard Atmosphere of 1962 (Ref. 2). Differences in model atmospheres are contained mainly in the description of aerosols. A summary of the atmospheric modeling is shown in Table III.

Aerosol density profiles for the different wavelengths in the 25-km meteorological range model atmosphere were taken from Elterman's 1968 Model Atmosphere (Ref. 3). Models with different meteorological ranges were produced by establishing the aerosol scattering coefficient for 0.55 μm which generated the desired meteorological range and applying an exponential variation to the aerosol scattering coefficient such that agreement with the 25-km meteorological range atmosphere was achieved at 5-km altitude. Aerosol size distributions were based on Deirmendjian's Haze C Model (Ref. 4).

For a meteorological range atmosphere of 25 km (and for 40 km for wavelengths of .4278 and 1.07 μm), the size distribution was defined as constant for radii between 0.03 and 0.1 μm, proportional to r^{-4} for radii between 0.1 and 10.0 μm and zero elsewhere. Size distributions for the 3- and 10-km meteorological range atmospheres differed only for radii in the range 0.1 - 10.0 μm where r^{-3} and $r^{-3.5}$ were used. For wavelengths of 0.5, 0.6, and 0.75 μm in the 40-km meteorological range model, the size distribution was defined as constant for radii between 0.02 and 0.1 μm, proportional to r^{-4} for radii between 0.1 and 20.0 μm and zero elsewhere. For all but three cases, a value of 1.5 - 0.01 was used as the index of refraction. For wavelengths of 0.5, 0.6, and 0.75, values of 1.53 - .004i, 1.53 - .006i, and 1.52 - .0095i

TABLE III. ATMOSPHERIC MODELING

I. AEROSOLS

A. DENSITY PROFILES

1. 1968 ELTERMAN MODEL ATMOSPHERE

2. EXPONENTIAL VARIATION WITH ALTITUDE IN HAZE LAYERS

B. SIZE DISTRIBUTIONS (HAZE C MODEL)

1. LOWER LIMIT OF CONSTANT REGION

a. .02 μm FOR .5, .6, AND .75 μm IN 40 km MR

b. .03 μm ELSEWHERE

2. UPPER LIMIT OF CONSTANT REGION = .1 μm

3. POWER LAW DECREASE

a. UPPER LIMITS

(1) 20 μm FOR .5, .6, AND .75 μm IN 40 km MR

(2) 10 μm ELSEWHERE

b. EXPONENT VALUES

(1) r^{-3} FOR ALTITUDES BELOW 5 km IN 3 km MR

(2) $r^{-3.5}$ FOR ALTITUDE BELOW 5 km IN 10 km MR

(3) r^{-4} ELSEWHERE

C. INDICES OF REFRACTION

1. $m = 1.53 - .0040i$ FOR $\lambda = .5$ μm IN 40 km MR

2. $m = 1.53 - .0060i$ FOR $\lambda = .6$ μm IN 40 km MR

3. $m = 1.52 - .0095i$ FOR $\lambda = .75$ μm IN 40 km MR

4. $m = 1.50 - .0000i$ ELSEWHERE

TABLE III. (CONTINUED)

II. ABSORPTION BY OZONE

A. FROM SELBY AND MCCLATCHEY FOR .5 AND .6 μM

B. NONE ELSEWHERE

III. ABSORPTION BY WATER VAPOR

A. FOR 1.07 μM IN 3, 10, AND 25 KM MR: U.S. STANDARD ATMOSPHERE 1962

B. NONE ELSEWHERE

were used when Mie calculations for the 40-km meteorological range model were made. These values were taken from an updated set of indices of refraction suggested by Fred Volz at the Air Force Geophysics Laboratory (Ref. 5) in a private communication.

Absorption by ozone was assumed only for wavelengths of 0.5 and 0.6 μm in the 40-km meteorological range model. Ozone profile data was identical to that used by Selby and McClatchey in 1972 in their LOWTRAN code (Ref. 6). Absorption by water vapor was assumed only for the 1.07 μm wavelength in model atmospheres having 3-, 10-, and 25-km meteorological ranges.

IV. CONVOLUTION AND POWER CALCULATIONS

The thermal power detected by a satellite-based receiver from an atmospheric nuclear event can be evaluated mathematically as a double integral.

$$P(\tau) = \int_{\lambda_1}^{\lambda_2} \int_0^{\tau} S(t,\lambda)\ I(\tau - t,\lambda)\ R(\lambda)\ dt d\lambda$$

Considering the inner integral a time convolution of the source and transmission for a given wavelength, the outer becomes an integration over wavelength of the product of the convolution results and detector response. The system being reported in this paper accomplishes these mathematical tasks.

When the atmospheric transmission of light, as generated by POLO, is to be used as a determining function in the convolution process, one of two procedures is followed.

If the convolution process is to be evaluated with the POLY program, results from a POLO run (as stored on tape) are sufficient. If a program from the TMTAU series is to be used, the scattered light intensity from a POLO run must be converted to the form shown in the following equation,

$$I(t:\lambda) = \sum_{i=1}^{6} a_i e^{-b_i t} + \sum_{i=7}^{9} a_i e^{-b_i t} ,$$

where t is retarded time in seconds and I is the intensity, for wavelength λ, in photons per second per unit area at the detector per source photon. Inclusion of the second term on the right is made to describe that light which has undergone a ground reflection; the term,

therefore, is applicable only for problems with nonzero ground albedos and then only for times which allow ground reflections. Since a sum of exponentials is not amenable to standard curve-fit processes (e.g., least squares), total automation of the conversion is not available. The necessity of user judgment in the evaluation of the coefficients in the above equation is the major disadvantage of using a program from the TMTAU series. The major disadvantage of using the POLY program is that statistical fluctuations which are removed by the curve-fit process remain, possibly producing errors which would be absent in TMTAU results. Any fluctuations can, of course, be removed by other processes, but currently are not.

The convolution process for a given wavelength λ is described by the integral

$$F(\tau,\lambda) = \int_0^\tau S(t,\lambda)\ I(\tau-t,\lambda)dt$$

where S is the time and wavelength-dependent source and I is the atmospheric transmission. Integration of this function, accounting for the detector response R as a function of wavelength λ, with respect to wavelength

$$P(\tau) = \int F(\tau,\lambda)\ R(\lambda)d\lambda$$

results in the power-per-unit area at the detector. This procedure is accomplished first by approximating the equation for $F(\tau,\lambda)$ with a sum of discrete values of both source and transmission in POLY and by use of discrete values for the source term and the curve-fit data for the transmission data in TMTAU. Evaluation of the detected power in TMTAU is made by fitting the results of the equation for $F(\tau,\lambda)$ with a wavelength-dependent exponential polynomial and evaluating it at the

discrete values of wavelength that are used to define the detector response $R(\lambda)$. In evaluating the equation for $P(\tau)$, POLY assumes that the detector response was contained in the source term

$$S'(t,\lambda) = S(t,\lambda) * R(\lambda)$$

and uses the trapezoidal rule. Calculating the product of the source term and the detector response can be accomplished with use of the program named RF2POLY if the source is the result of a RADFLO run. Reduction of the size of the time mesh used in RADFLO and units conversion can also be accomplished by RF2POLY.

As an example of the effectiveness of the TMTAU and POLY codes, an analytic problem was solved. Both source and transmission were directly proportional to wavelength and exponentially decreasing in time. Although not a realistic problem, the results shown in Fig. 6 demonstrate the ability of both programs to perform the required mathematics. At times greater than 5.5 μsec, the POLY and TMTAU calculations were in excellent agreement with the analytic solution.

To illustrate the results of a realistic problem, a version of TMTAU which optionally generates a spectral source based on blackbody theory and scaling laws proposed by Tom White (Ref. 7) was used. These scaling laws are applicable to total energy yields above 1 KT and burst altitudes below 15 km. Derived from both field data and theory, the scaling laws provide a fast and fairly accurate method of source modeling. The results shown in Fig. 7 are for an event of 2 KT at 3 km altitude in a 25-km meteorological range atmosphere. A wide-band silicon detector, based on a satellite at synchronous altitude, directly over the event was assumed. POLO data for a ground albedo of 0.4 and for wavelengths of 0.4278, 0.75, and 1.07 μm was used from the data pool. Results from a TMTAU calculation assuming a source generated by the RADFLO code for the same event are also shown in Fig. 7 for comparison.

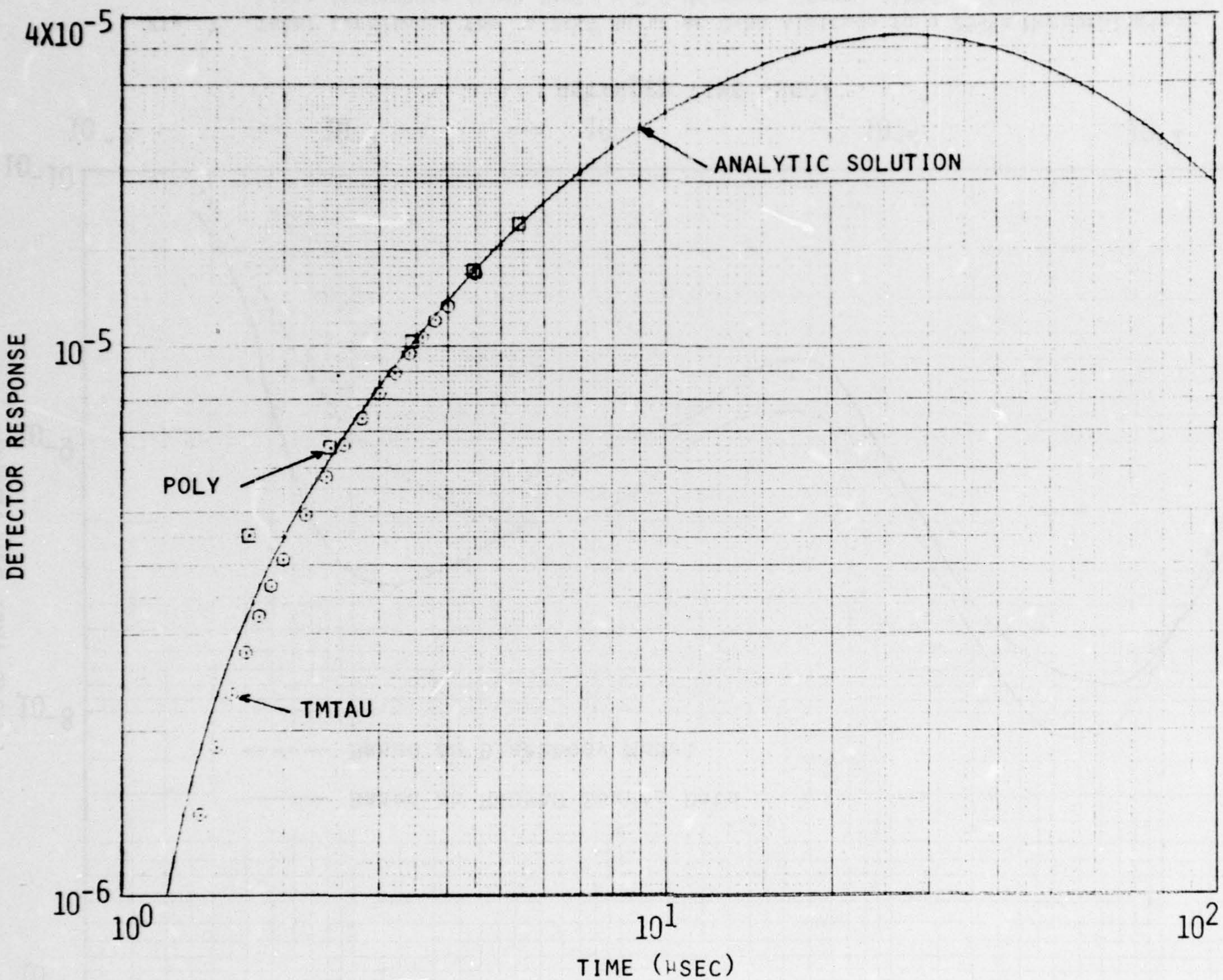


Fig. 6. Comparison of POLYN and TMTRF01 Results for Test Problem: Lower Time Value for Source Function = 10^{-6} sec in all Solutions

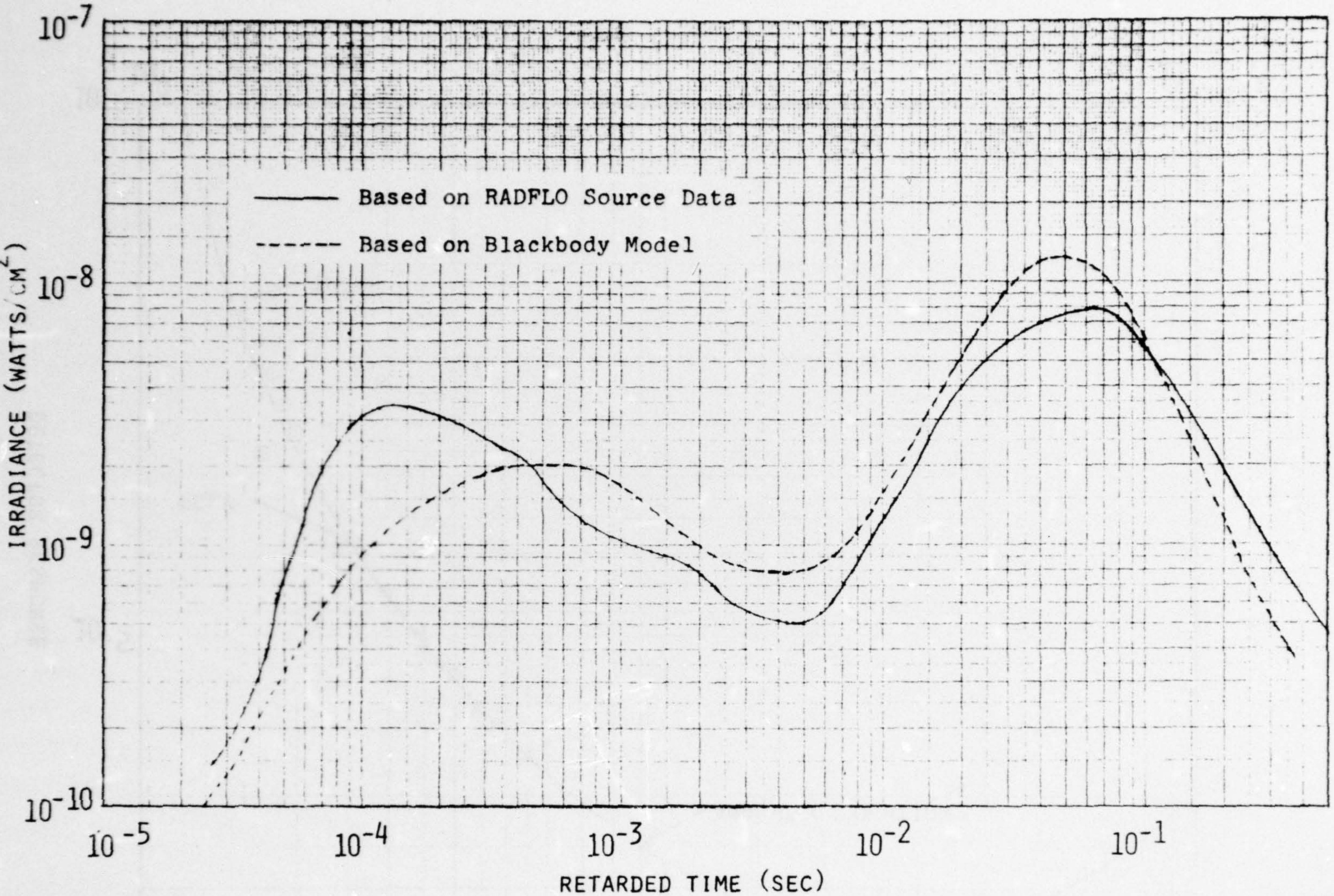


Fig. 7. Total Irradiance from a 2-KT Burst at 3-km Altitude in a 25-km Meteorological Range Atmosphere (Look Angle = 0.0 degrees, Ground Albedo = 0.4)

V. CONCLUSIONS

A method of predicting the thermal radiation power detected by a satellite-based receiver resulting from an atmospheric nuclear event is currently available.

The data pool of atmospheric transmission provides the accuracy of extensive Monte Carlo studies which can be augmented as needed by additional POLO calculations. Approximations to the source term are available (through blackbody theory and scaling laws) to establish rapid estimates while more exacting source terms (e.g., RADFLO or experimental data) can also be used. Time-dependent atmospheric transmission data as generated with the POLO procedure can be used as either discrete values in the POLY procedure or as continuous function approximations in the TMTAU procedure. Segmentation of the method allows both minor refinements and major modifications without disrupting the entire system.

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